Mission Planning and Monitoring for Heterogeneous Unmanned Vehicle Teams: A Human-Centered Perspective

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Future unmanned systems in the military will be highly heterogeneous in nature, with vehicles from multiple domains—aerial, underwater, and land—working in collaborative teams to complete a variety of missions. The complexity of supervising these teams will be enormous and will rely on human creativity, judgment, and experience. Therefore, the design and development of mission planning and monitoring technologies must be rooted in a deep understanding of the human operator's role as mission manager, and must effectively address the reasoning skills and limitations of both the human and autonomous intelligent system. In this paper we present our work to approach these supervisory issues from a human-centered perspective. We first review the findings of a cognitive task analysis, through which we defined critical informational requirements and developed display interfaces for human operators developing and executing mission plans for a small team of underwater and aerial unmanned vehicles. These findings raise several operations issues for unmanned vehicle management, namely (1) vehicle and task heterogeneity and (2) the coordination of command and control across a vehicle team. We discuss the impact of both of these design requirements on the human-centered development of mission planning tools for unmanned systems. Finally, we introduce an investigative approach to support the rapid evaluation of interfaces that flexibly accommodate alternative command and control philosophies for heterogeneous automated systems using a combination of modeling and human-in-the-loop evaluation processes

I. Introduction

Future naval operations in the littoral environment are expected to make extensive use of coordinated unmanned vehicle teams to support a range of operations, including intelligence, surveillance, and reconnaissance (ISR), as well as anti-terrorism/force protection (AT/FP), suppression of enemy air defenses (SEAD), and anti-mine and anti-submarine warfare (AMW, ASW). [1, 2] While great strides are being made in the development of unmanned aerial, undersea and surface vehicles (collectively UVs), the development of advanced operational capabilities that will effectively support the autonomous operation of heterogeneous teams of these vehicles with minimal human intervention is proceeding more slowly. Within the scope of the Intelligent Autonomy program, the Office of Naval Research (ONR) is pursuing technological advancements to support future operations in the littoral environment by developing advanced autonomous mission planning and execution technologies for heterogeneous teams of UVs. One significant goal of the IA program is to *maximize the vehicle to operator ratio* of such heterogeneous UV teams to effectively transition the human operator's role from an *in-the-loop* controller to a supervisory manager, or *on-the-loop* controller.

While many future unmanned systems will reduce the extent to which human operators engage in direct, manual control of vehicle behaviors, humans will still be deeply involved in planning, higher-level operation, and

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contingency intervention (including coping with system failures). Therefore, any system of so-called "unmanned" vehicles will remain a manned system. This concept of coordinated control between human operators and automated platforms is described as a *mixed-initiative* team. Within mixed-initiative teams, the transition of the human's role from manual to supervisory control introduces a new layer of cognitive complexity, which stems from the need for effective communication between human operators and multiple autonomous mission planning and execution systems. Mission planning for mixed-initiative teams—both prior to and during actual execution—is an inherently human process that can be aided by automation but must always depend on human strengths of creativity, judgment, and experience, while guarding against decision biases and error. Within future mixed-initiative systems, operators will be expected to manage multiple tasks at once, such as mission planning/replanning and mission monitoring, for vehicles in the air, under and on the water, and on land. However, increases in the number of available information sources, the volume of incoming information, and operational tempo—all of which contribute to the overall cognitive demand placed on operators—could become limiting constraints to the success of these network-centric processes.[3] Therefore, the design and development of technologies supporting the supervisory control of unmanned vehicle teams must be rooted in an understanding of and respect for the human's role as mission manager. As a wide variety of highly-automated vehicle platforms and sensor packages become available, designers will need to address the new functionality these systems afford through a human factors-based process that maximizes human capabilities when leveraging these resources.

In particular, two major concerns regarding the development of interfaces for human supervision of unmanned vehicle teams are explored in this paper: (1) the heterogeneity of assets within the unmanned team, and (2) the allocation of heterogeneous team assets and task responsibilities amongst multiple operators.

With respect to heterogeneity**,** the US Navy is targeting the deployment of numerous types of unmanned vehicles within the future littoral environment. In this example, heterogeneity not only refers to the simultaneous deployment of aerial, surface, underwater, and ground vehicles that operate in different physical domains, but also implies the integration of unmanned assets with different operational capabilities, sensor packages, and levels of intelligent automation. To successfully address these types of heterogeneity, it will be crucial to avoid typical system engineering approaches in which human-machine interaction is designed for very specific and isolated vehicle capabilities. Such development processes result in stovepiped systems that cannot be easily integrated to support long-term interests for coordinated mission operations in multiple domains or across multiple platforms. Rather, we believe that success lies in providing unified human/machine interfaces that support an operator's seamless interaction with the full range of targeted vehicles and tasks and are carefully targeted to minimize the cognitive costs of rapidly switching between these. Only by accommodating this seamless integration in the initial design process and then layering the specific vehicle interaction requirements on top of that design, will it be possible to support the ultimate goal of integrated mission operations.

Most designs for controlling unmanned vehicles reflect an assumption that deployment will occur in an isolated operational environment where a single operator (or even small group of collocated operators) will be independently responsible for managing a team of independently "owned" vehicles. However, it is more likely that large-scale missions will require the deployment of multiple teams of unmanned assets from multiple distributed command and control platforms, and mission management will be a coordinated and collaborative process across these integrated human and semi-autonomous teams. To address this issue of coordination, our strategy must accommodate the notion of multi-platform/multi-asset allocation into the human factors-based design process from the start. Unfortunately, there is a lack of clarity throughout the unmanned systems community about the exact nature of such strategies for supervisory allocation. Therefore, it is critical that any approach to enable a flexible design and development process support examination and evaluation of a range of approaches to command and control allocation across multiple operator teams.

In this paper, we present the initial results of work undertaken to address these issues from a human-centered perspective. We first review the results of a preliminary analysis and design effort aimed at developing effective and efficient displays for supervising simple unmanned vehicle team within a littoral combat environment. This example shows how informational requirements critical to supporting human operators in the development and execution of mission plans may be defined for a particular mixed-initiative team and illustrates how these informational requirements can be leveraged in the design of display concepts to support these informational requirements in an efficient and effective manner with respect to the mission context. The findings from this initial analysis and design effort point to the importance of several outstanding questions regarding issues of collaboration and control allocation in the management of heterogeneous unmanned vehicles. We discuss the impact of these issues on the development of mission planning tools for unmanned systems from a human-centered perspective. Finally, we introduce an investigative, simulation-based approach for the rapid evaluation of multiple candidate interface designs that accommodate alternative command and control philosophies for heterogeneous automated systems. We

are currently using this approach to perform human-centered design and development that targets the human operator's ability to interact collaboratively with both unmanned systems and other distributed human operators.

II. Developing Mission Planning and Monitoring Interface for an Unmanned Vehicle Team

Approaches to mission management for mixed-initiative operations typically center upon visual interfaces designed to support a single human operator controlling a single vehicle. Future unmanned operations, however, will require supervisory interfaces that allow a single operator to manage a team of multiple vehicles working to complete one or more tasks simultaneously. Here, we describe a preliminary effort to design a human-centered display interface for managing a simple team of unmanned vehicles in a limited operational context. We first describe the analytical methods employed to determine the informational and task-related requirements such an interface would need to support, and then present an overview of the design implementations used to address these requirements.

A. Identifying Information Requirements through a Hybrid Cognitive Task Analysis

One significant hurdle to the development of interfaces for novel or futuristic systems is establishing a sufficient understanding of how those interfaces will be used in the fulfillment of particular operational demands, including who will use them, what context they will be used in, and what specific tasks they will support. Various approaches to cognitive tasks analysis (CTA)[4] have been proposed and demonstrated for deriving information requirements and interface design concepts for systems that already exist in some form. However, most established CTA techniques are difficult to apply in the design of novel, futuristic systems for which no subject matter experts, documentation, or previous system implementations exist.[5, 6] In our design effort, the goal was to develop interfaces to support a single operator controlling a team of multiple unmanned vehicles—something infeasible with existing technical capabilities, limiting the effectiveness of traditional CTA approaches. To address these limitations, a multi-tiered approach to CTA was developed and used, drawing upon several distinct analytical methods. Details concerning the specific methods of this "hybrid" CTA approach are described by Ref. 7. Here, we summarize the previously-reported application of these techniques to the current design problem and provide an overview of the resultant analytical outputs.

Prior to executing the hybrid CTA process, we developed a detailed description of an operational activity scenario describing operator roles and unmanned vehicle tasks and behaviors in completing a particular mission. This scenario described the manner in which a supervisory interface would be leveraged to plan, monitor, and adapt unmanned vehicle behaviors in the fulfillment of a particular combat mission, and was used to ground the generation of information requirements through the hybrid CTA process. While futuristic in nature, the operational scenario was intended to be realistic in scope and sufficiently detailed to clearly identify the supervisory operator's anticipated responsibilities with respect to tasking the system of unmanned vehicles, understanding proposed mission plans to achieve that tasking, and monitoring the mission execution against those generated plans. Briefly, this scenario involved a single human operator's supervision of a team of unmanned underwater vehicles (UUVs) performing clandestine ISR operations within an enemy harbor. The unmanned vehicle team was comprised of two UUVs responsible for entering the harbor, obtaining surface imagery, and tracking targeted vessels, as well as two UUVs that served as sentries at the harbor's mouth. In addition, communications between the UUVs and the human operator were supported by an unmanned aerial vehicle (UAV) on a shared network. Although the scenario was fairly limited in scope, it did exhibit some key qualities of heterogeneity anticipated for future unmanned operations, including multiple tasks (imaging, tracking, communications support) and vehicle domains (underwater, air).

Based on this limited operational scenario, a hybrid CTA was performed to generate the functional and display requirements for a supervisory interface that would allow a single operator to coordinate the control of four UUVs via a UAV communications link. The hybrid CTA process began with the definition of a Scenario Task Overview, through which the operational scenario described above was first separated into distinct phases, with boundaries marked by changes in the operator's anticipated goals, tasks, and behaviors. These individual phases were then further decomposed, with anticipated sub-goals and sub-tasks enumerated using a hierarchical structure. Through this process, three primary mission phases were identified and described: (1) mission planning, (2) mission execution, and (3) vehicle recovery. Within these phases, a total of 25 distinct mission sub-tasks were identified and described in detail.[8] A partial example of the Scenario Task Overview—a description of the mission execution phase of the operational scenario—is provided in Table 1.

Table 1. Scenario Task Overview for Mission Execution Phase.

UUV Team Harbor ISR Scenario **Phase 2: Mission Execution**	
Phase Goals	**Phase Breakdown**
1. Launch UUVs	• Launch Search UUVs • Launch Sentry UUVs
2. Acquire Target	• LCS tracks progress of UUVs, making sure UUVs are at expected positions at scheduled checkpoints (geo-fix should update actual location) • LCS tracks status & availability of UAV (ongoing) • Search UUVs surface to scan shoreline at planned location/time (updated geo-fix position data sent via UAV, if UAV is in range) • If ATR flags an image during a Search UUV scan, EO imagery is sent to LCS via UAV. If UAV unavailable, UUV loiters, resurfacing and resending at next scheduled checkpoint. Continue until UAV is available. Once EO imagery is sent, UUV loiters until Acknowledgement (Ack) is received from LCS – surfacing at each scheduled checkpoint. • LCS examines EO-imagery, then sends Ack back to all UUVs. If Ack is positive, UUV continues to loiter in current position, monitoring confirmed target. If Ack is negative, UUV resumes search task. • Phase is complete once one of the UUVs has received a positive Ack from the LCS. Second Search UUV should be retasked to confirmed target location for redundant monitoring (or retasked to another potential target or returned to LCS)
3. Monitor Target	• Search UUV should continue to surface at scheduled checkpoints to continue monitoring target – ATR should continue to flag target as contact of interest and update imagery. • When onboard ATR no longer has target in camera range, target tracking should be handed off to UAV. Last known location should be available to Sentry UUVs, to UAV's MTI program, and to LCS. • When target is lost by Search UUV(s), Sentry UUVs, UAV (if available) and LCS should be given the last known location by the UUV as well as historical and predicted track of target. • Phase is complete once UAV is tracking the target, or Search UUVs handoff to Sentry UUVs. • LCS should retask or recall Search UUVs
4. Track Target	• UAV should use last known location from UUV + MTI software to track target. UAV should send LCS MTI feed. • LCS should monitor LCS MTI feed. • LCS should determine estimated time of arrival of target at harbor entrance based on MTI feed from UAV and schedule Sentry UUVs to surface and capture EO-imagery of expected target location at that time via UAV communication link (this should be automated to the highest degree possible). • Phase is complete once target reaches Sentry UUVs. UAV tracking could be discontinued at this time.
5. Exit Harbor	• Within a predetermined window of time, Sentry UUVs should surface and wait for target arrival. • UUV should capture and send collected EO-imagery to LCS via UAV. If UAV is unavailable, surface at scheduled time intervals to retry EO-imagery transmission. Continue cycle until Ack is received from LCS. Regardless of Ack status, at least 1 UUV will track the target out of the harbor based on a set of predetermined criteria. • LCS should determine tracking profile of Sentry UUVs and determine when they will be retasked or recalled.

Following the decomposition of tasks within the Scenario Task Overview, an Event Flow Diagram was created to analyze and capture the temporal constraints of the selected mission scenario. These temporal constraints govern when particular events or control activities must occur within the context of the overall mission, particularly in relation to other events. An example of an overview-level Event Flow Diagram for the entire mission scenario is shown in Figure 1, on the following page. The Event Flow Diagram depicts three basic classes of events relevant to the supervisory control of unmanned vehicles: loops, decisions, and processes. Loops (L) represent automated processes that will potentially continue in an iterative fashion until some pre-determined event occurs. Decisions (D) represent events that require some type of knowledge-based input from the human supervisor before a particular vehicle behavior continues or changes. Processes (P) are situations requiring some form of human-computer interaction beyond simple decision-making to support a mission subtask. In this example, these event classes are labeled for cross-reference with subsequent products of the hybrid CTA process.

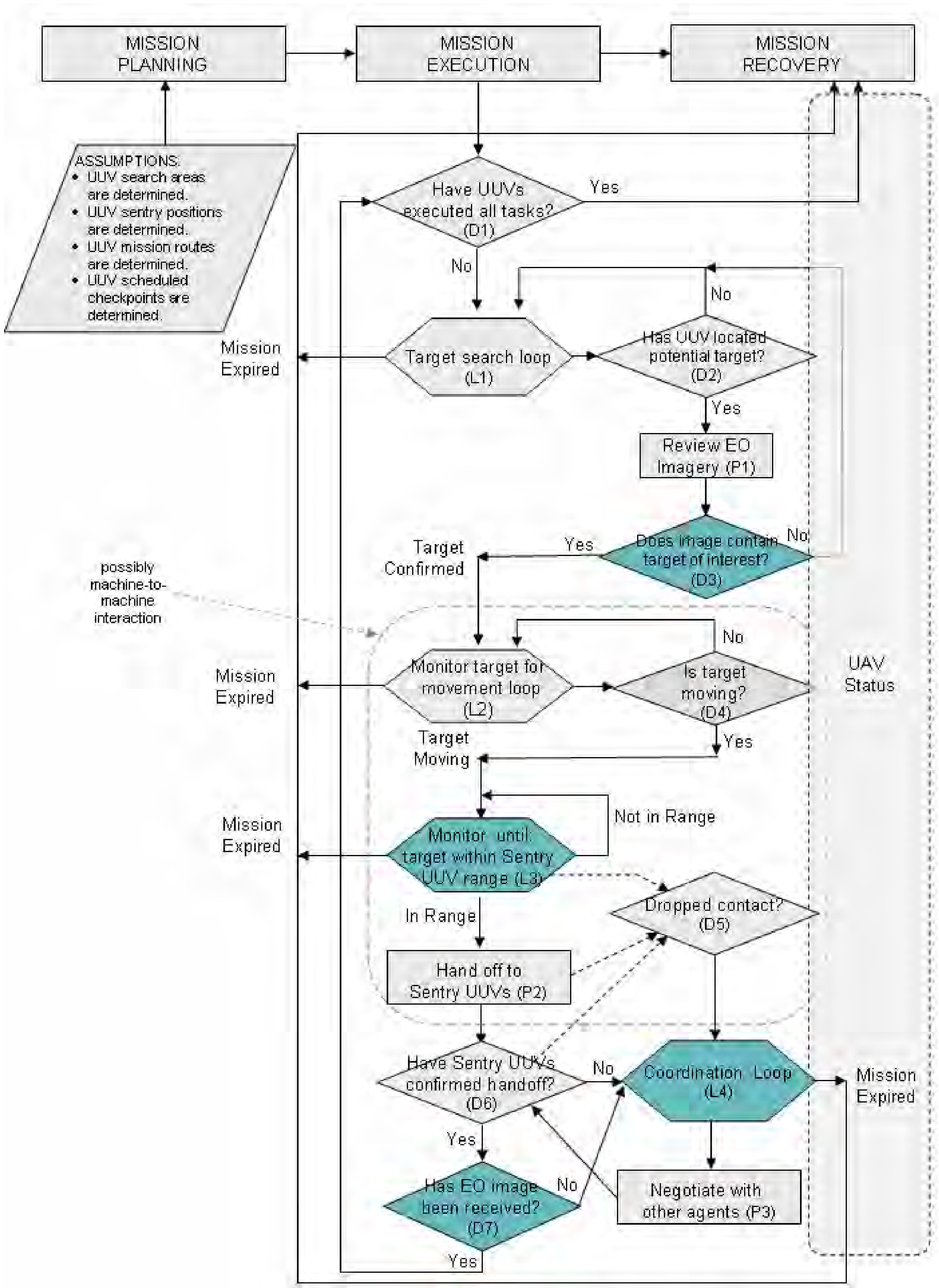


Figure 1. Event Flow Diagram for UUV control during the mission scenario

Drawing on the temporal description of the mission phase sub-tasks, a Situation Awareness (SA) Requirements analysis was performed. This analysis used traditional methods to generate SA requirements for each of the three SA levels: perception, comprehension, and projection.[9] For each of these levels, the analytical team specified the situation awareness requirements for each of the mission phases and associated sub-tasks identified by the Scenario Task Overview. A partial example of output of this process is shown in Table 2.

Table 2. Scenario Task Overview for Mission Execution Phase.

UUV Team Harbor ISR Scenario **Phase 2: Mission Execution – Acquire Target**		
Level 1: Perception	**Level 2: Comprehension**	**Level 3: Projection**
• Visual and audible alert when UAV leaves or returns to on-station duty (D2)	• Error/alert message clarification (L1, D2, P1, D3)	• Schedule of estimated UAV on-station availability should be provided on a visual timeline (D2, D3) • Uncertainty of estimated timeframes should be indicated on availability timeline (D2, D3) • Potential missed communications points (D2, D3) • Future likely UUV tracks (D2, D3) • Vehicle limitations (when predicted to exceed some safe region) (D3) • UUV schedules (D2, D3) • Prediction of system health/status (D2)
• All agents' position information (D3) • Hazardous areas (L1, D2) • Geo-spatial boundaries (L1, D2)	• Vehicle limitations (on demand) (P1, D3)	
• Indicate communications link coverage range when on-station (D2, D3) • Sensor coverage should be visualized on tactical map (D2, D3)	• UUV schedules (D2, D3) • Health and status of UUVs (L1, D2)	
• Visual/audio feedback for confirmation of target acquisition (D2, L1, D3)	• Strength of comms link to UUV scheduled to check in should be indicated on tactical map (based on current position of UAV and comms range) (D2, L1, D3) • Expected connection should be indicated at UUV scheduled checkpoint time – if UAV out of range / unavailable, missed connection should be indicated (L1, D2) • Temporal constraints (P1)	

Finally, a Control Task Analysis[10] was performed to analyze potential behavior of the human operator at each of the decision processes outlined by the Event Flow Diagram. Separate Decision Ladders[11] were used to capture the states of knowledge and information processes required by the human operator to perform these component decisions. These decision ladders were then augmented with design concepts describing how the steps within each ladder could be supported by an information display, as well as alternative automation implementation strategies. An example of one such augmented decision ladder from this analysis is shown in Figure 2, on the following page.

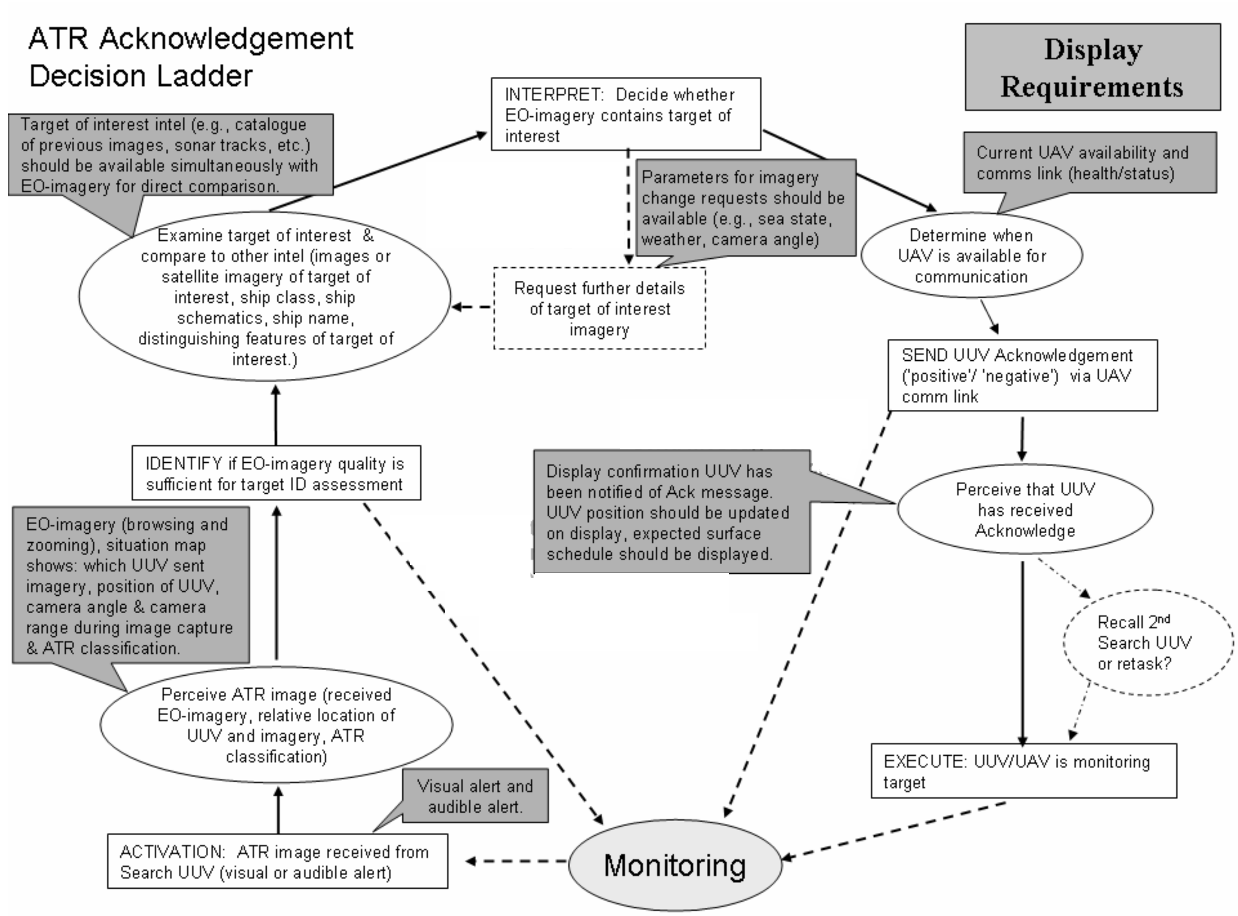
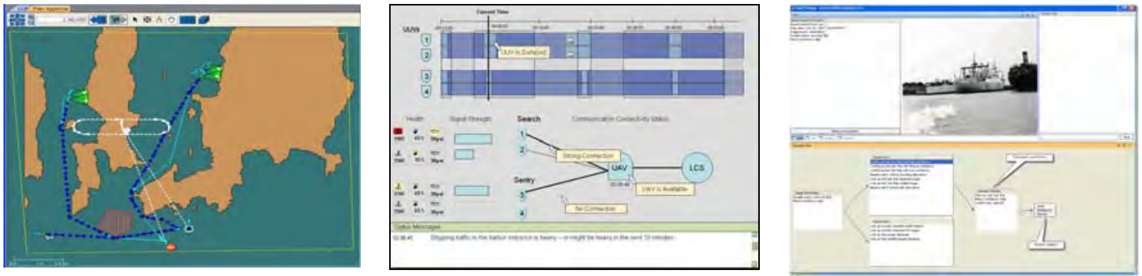


Figure 2. Example of a Decision Ladder for the ATR Acknowledgment decision (D3) within the Acquire Target sub-phase of Mission Execution.

B. Transforming Information Requirements into Interface Design Concepts

Based on the outputs of the hybrid CTA described above, a detailed HCI design was developed to support a single operator supervising control of the unmanned vehicle team depicted in the mission scenario. This supervisory interface was designed to provide a suite of advanced visualization tools that increase the operator's ability to intuitively understand and manipulate the scheduled activities, or plans, of multiple unmanned vehicles involved in a mission by addressing the information requirements and decision-making processes outlined through the hybrid CTA. The interface consists of three primary displays, presented in parallel across multiple display monitors, as shown in Figure 3, on the following page. These displays are: (1) a Map Display, (2) a Health and Status Display, and (3) a Task Display. The content and structure of the information provided to the operator through each of the three unique displays was governed by the information requirements and task activity insight generated by the hybrid CTA process, while the graphical mechanisms used to present this information was informed by human-centered design principles. In particular, informational resources were distributed across multiple displays in an attempt to allocate common supervisory control activities and to preserve operator SA by reducing the extent to which discrete tasking operations obscure the availability of continually evolving mission data and world state information.



Map Display Health and Status Display Task Display

Figure 3. The three component displays developed to support supervisory control of the notional unmanned vehicle team described by the operational scenario.

The interface's Map Display (Figure 4) was designed to marshal geospatial information relevant to the entire mission into a single display. This display allows the operator to see the positions of the UAV and UUVs—as well as the positions of other known or estimated entities, including blue, red, and neutral vehicles—in relation to the operational area and the command and control platform. At the operator's discretion, the Map Display can also depict specially defined geospatial regions such as "no-swim" or "no-communication" zones, planned and traversed vehicle routes, current and predicted target locations, or other mission-relevant elements with spatial properties. These additional layers can be toggled using a display filter menu, which allows the operator to quickly and easily create customized display interfaces that depict the most relevant and useful information—or hide the most extraneous or distracting information —for supporting awareness, reasoning, and planning during the evolving mission. Because unmanned vehicles may be operating in many domains simultaneously for a given mission (e.g. water surface, underwater, air, land) there will be a need for the operator to flexibly examine the information most relevant to the particular vehicle or task that is being attended to at any given time. For example, when the operator is planning or evaluating potential UUV routes, local bathymetry data can be added to the Map Display. This bathymetry data can then be removed to reduce clutter when the operator is interacting with a UAV asset, at which time it may be more relevant to display topological data, or anti-aircraft threat zones.

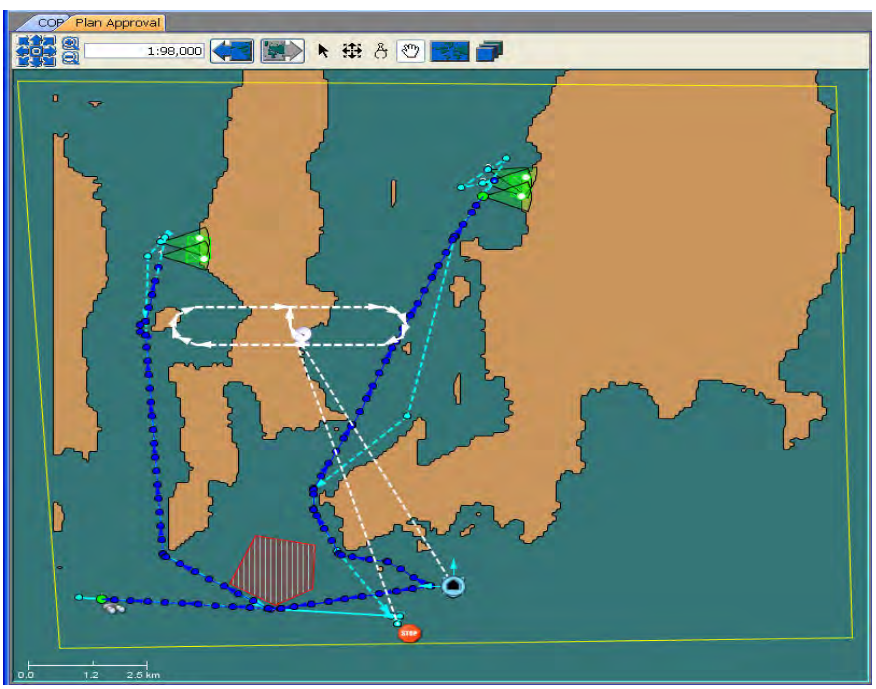


Figure 4. Map Display.

The Health and Status Display (Figure 5) provides an overview of the situational information most critical to the operator's supervisory control of the mixed-initiative team. This includes relevant operating parameters from individual vehicles, such as internal temperature, oil pressure, and remaining fuel level. Also depicted is the communication status between the vehicle team and the command and control platform. In this case, a network diagram depicts communications from each UUV being routed through the single UAV to the base of operations aboard a Littoral Combat Ship (LCS). The diagram is augmented to depict the strength of the wireless connection between each vehicle, allowing the operator to quickly ascertain the overall status of communication between the entire team while performing monitoring, troubleshooting, or re-planning activities.

At the top of the display, a plan timeline allows the operator to see the linked, temporal constraints of future and executed mission plans at a glance, while providing drill-down access to detailed timelines for each vehicle. The timeline is augmented to display additional mission data in a number of ways. For example, color-coded regions indicate UUV status (e.g., dark blue for submerged, light blue for surfaced); bounded areas indicate times during the mission when the UAV will be able to serve as a communications link for ISR download, decision acknowledgement, or re-tasking; icons show planned or completed task activities, such as ISR image collection. Finally, in addition to providing overall health and temporal status indications, all major alarms—such as low vehicle fuel levels, unexpectedly lost communications links and missed mission deadlines—are also routed through this main display window.

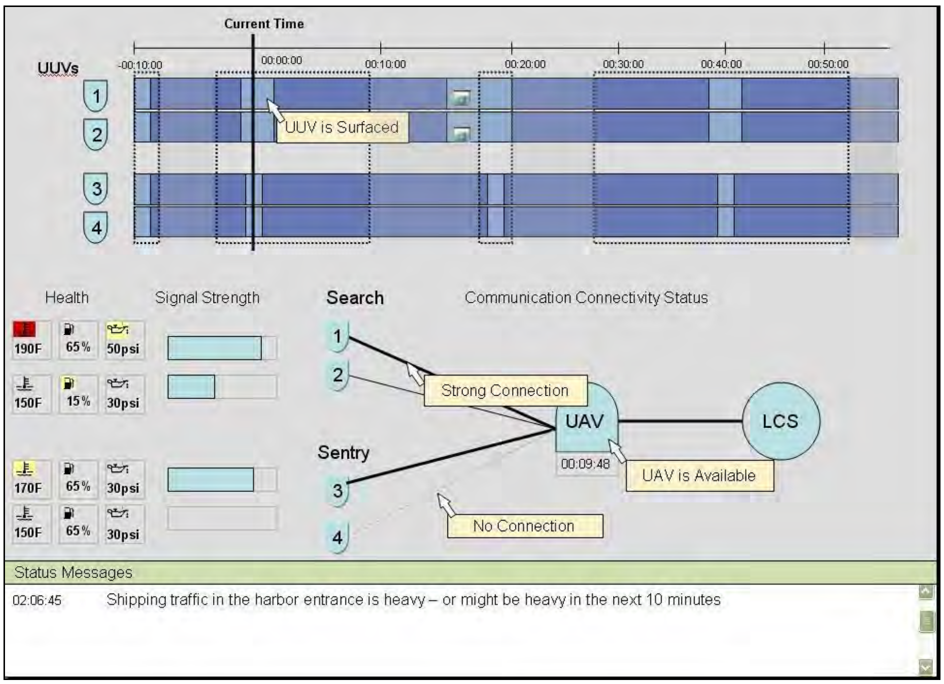


Figure 5. Health and Status Display.

The Task Display, (Figure 6) collates detailed, fine-grained information for decision-making and task-level vehicular control in a single location, separate from the Map and Health and Status displays. The Task Display allows the operator to make decisions based on information transmitted by the vehicles' sensor packages and control the current and future actions of each unmanned vehicle. For example, it displays ISR images received from individual UUVs and supports the operator in reviewing and performing related mission actions on those images (such as verifying that a UUV has in fact located a particular target, or requesting additional EO imaging). This multifaceted, user-configurable interface also allows the operator to collaborate with other mission operators or the commander, and to define or update mission tasks and vehicle behavior parameters (e.g., minimum approach distances for obstacles or targets, maximum wait time before surfacing for radio check-in).

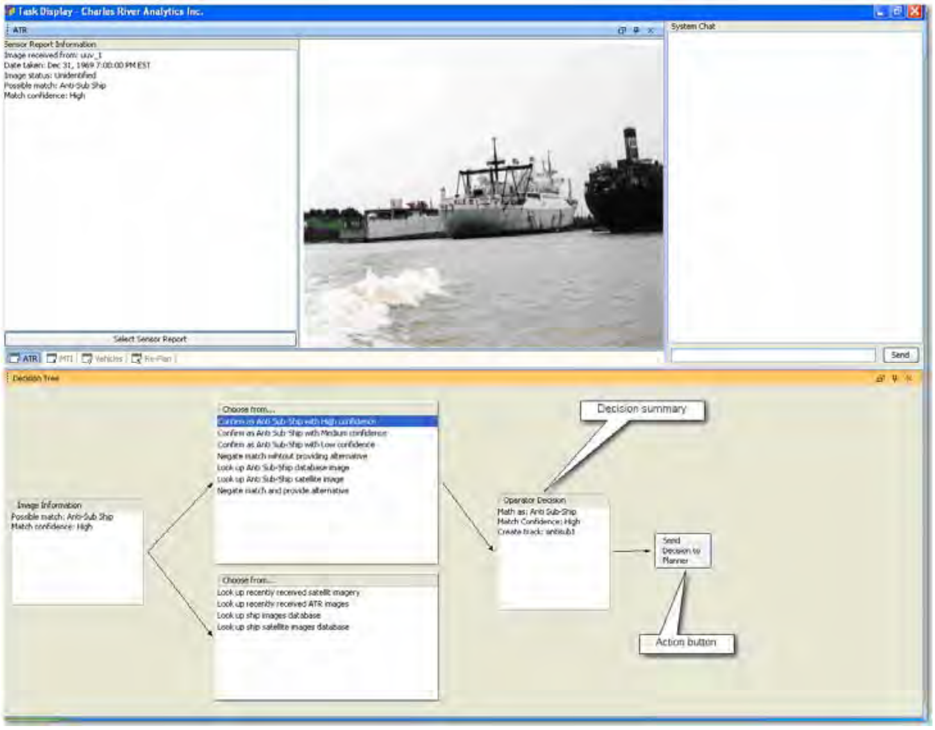


Figure 6. Task Display.

One key component of the Task Display is the Dynamic Contextual Decision Tree control interface (DCDT)[12]. This interactive display component (Figure 7) dynamically adapts the supervisory control options available to the operator to address the context of particular mission tasks, and presents the operator with two types of information: (1) actions reflecting a supervisory decision to be made by the operator, and (2) actionable information sources which may support the operator in better making this required decision. For example, in this particular mission scenario, the UUV automated target recognition (ATR) system captures an image of a vessel within the harbor and identifies the vessel as the SS Windsor. Mission requirements necessitate that the human supervisory controller verify all target recognition tasks. In this case, the DCDT interface provides image information to the operator (e.g. “Possible Match: SS Windsor; Confidence: High”) and then gives the operator a choice of actions regarding the confirmation of this targeting activity (e.g. “Confirm as SS Windsor with High confidence”, “Confirm as SS Windsor with Medium Confidence”, etc.), or context-sensitive actions that will help them make a confirmation (e.g. “Look up SS Windsor in ship images database”). The DCDT is dynamically branched to reflect subsequent actions by the operator. For example, selecting the control action “Negate match and provide alternative” results in new “Choose from…” lists, including alternative control actions (e.g. “Confirm as SS Vincence”, “Confirm as Other”) or a pruned alternative action list (e.g the “Look up SS Windsor” options are removed from the list).

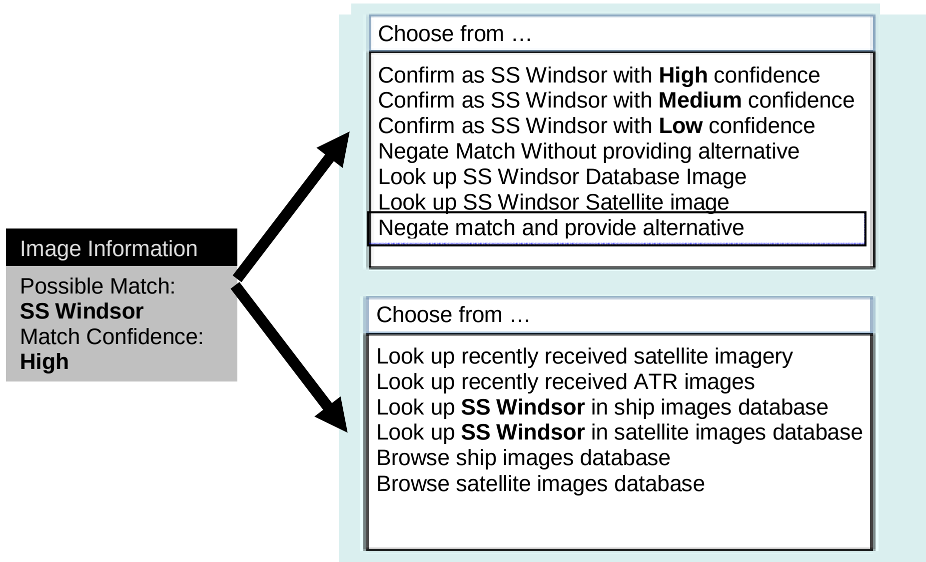


Figure 7. Example of a Dynamic Contextual Decision Tree (from Nehme, 2006), that allows the operator to perform a confirmation task (top) or an action that helps them perform this task (bottom).

III. Addressing Heterogeneity and Control Allocation in the Supervision of Complex Unmanned Vehicle Teams

While there is currently increasing interest within the Navy to determine system architectures that would allow one person or a small team of people the ability to control multiple, heterogeneous unmanned vehicles, there has been virtually no discussion of what really constitutes heterogeneity, particularly from a human cognitive aspect. For example, heterogeneous operations could include vehicles from different physical domains (i.e., UAV,USV, UUV, etc.), which are likely to vary significantly in their physical operation. However, multiple vehicles within the same domain—even those based on the same platform—can also exhibit heterogeneity with respect to the sensors and weapon packages each individual vehicle carries. Vehicles may also differ across a wide range of intelligent autonomy capabilities, requiring interaction that ranges from remote teleoperation via “stick and throttle” control, to “fire and forget” monitoring of highly autonomous platforms capable of mission planning and execution with only high-level objective-oriented guidance from human operators. It is likely that all three of these types of heterogeneity—operating domain, performance/payload capabilities, and automation capabilities—will impact the manner in which a human operator interacts with individual vehicles comprising the team.

Beyond differences in the physical and operational characteristics of individual team vehicles, human operators may also experience heterogeneity that arises from the assignment of these vehicles to particular mission tasks, as well as the allocation of these vehicles/tasks across one or more operators—issues related more closely to concepts of operations than actual differences between vehicles. For example, task heterogeneity may occur if an operator is responsible for supervising two unmanned vehicles, each of which is performing separate, distinct mission tasks. This heterogeneity would require the operator to make a cognitive switch between the specific requirements and constraints of each task when shifting attention between vehicle teams—something that would not be required if both vehicles were engaged in the same task. Similarly, heterogeneity of location may occur if an operator is tasked with controlling two UUV teams operating in different geographical locations.

Our initial cognitive task analysis and interface design effort, described in the previous section, focused on a simple unmanned vehicle team composed of four identical UUVs performing a search and sentry operation and one UAV providing communications support. Although this team reflected some qualities of the domain, task, and vehicle heterogeneity that is anticipated for future unmanned naval missions the complexity of this heterogeneity was fairly limited. Even so, differences between the tasks, vehicle capabilities, and operating demands across this simple multi-vehicle team had a great impact on the supervisory responsibilities of the human operator, as well as the ways in which the operator could interact with the unmanned system to adapt mission behaviors. This, in turn, affected the information requirements of the interactive display supporting effective supervisory control, as well as

the particular mechanisms selected to convey these information requirements and control opportunities to the human operator for mission management. Throughout the interface design effort, it became increasingly apparent that significant challenges arise when creating display interfaces capable of flexibly supporting highly heterogeneous unmanned vehicle teams and mission objectives. This is because the cognitive tasks placed upon the operator during a particular operation are tightly coupled to the specific vehicle (or vehicles) performing individual mission tasks, the capabilities of the automation supporting vehicle behaviors, and the allocation of tasks and vehicles across the supervisory team. Therefore, it cannot be assumed that the previously described interface, which was developed to address the cognitive challenges facing a single operator supervising five particular unmanned vehicles to perform a specific operational task, would appropriately support an operator controlling a different team of heterogeneous vehicles. Nor would the interface necessarily support the same team of vehicles completing different operational tasks, or multiple operators collaboratively sharing vehicle control.

The tight coupling between mission tasks, vehicle team configuration, and operator supervisory control allocation raises numerous questions regarding the design of effective displays for managing complex unmanned vehicle teams. For example, will it be feasible to create a single, generic display environment that is capable of flexibly supporting the supervisory control of any unmanned vehicle in performing any mission task? If not, will it be necessary to create unique interfaces for every distinct vehicle domain (e.g. air vehicles vs. underwater vehicles)? For every distinct vehicle type (e.g. UAV X vs. UAV Y)? For every vehicle/task combination (e.g. a UUV performing surface imaging, vs. the same UUV performing bottom mapping)? If highly-specialized supervisory interfaces are required, will it be possible to leverage common display elements and interaction techniques in a manner that allows human operators to easily traverse multiple vehicle/task configurations? Could such displays be designed to avoid or minimize coordination problems and the cognitive complexities of distributing supervisory control across multiple, highly stove-piped interaction systems during complex multi-vehicle missions?

These questions highlight the important roles in determining optimal interface design that are played by (1) mission heterogeneity, and (2) alternative strategies for vehicle/task allocation across multi-member supervisory teams. In the remainder of this section, we introduce a notional scenario that we have developed to flexibly investigate these issues of heterogeneity and control allocation strategies on the design of interfaces for supervising unmanned vehicle teams. We then describe the methods we are implementing to effectively target the design of future supervisory control interfaces by augmenting the previously described hybrid CTA approach with modeling and prototyping efforts that analyze where these heterogeneity and allocation issues may present the greatest cognitive challenge to the operators and then design and evaluate interfaces that address these complexities.

A. Heterogeneity of Future Unmanned Missions

To support a more detailed investigation of these issues, the mission scenario described earlier in this paper was extended to better reflect multiple forms of mission heterogeneity relevant to human supervisory control. Although this new scenario is quite complex (and far reaching, given the technological capabilities and integration of existing unmanned platforms), it reflects numerous attributes of heterogeneity that are anticipated within futuristic unmanned vehicle teams and provides a rich environment for exploring the cognitive impact of heterogeneity on operator performance and interface design requirements.

In this notional scenario, depicted visually in Figure 8, a US Navy Littoral Combat Ship (LCS) is stationed offshore in international waters and tasked with preparing to insert a team of Special Operations Forces deep within an enemy harbor. Prior to the SOF insertion, the LCS launches a team of recoverable UUVs to perform reconnaissance on the planned insertion route and landing site. This team includes one submersible (UUV1) with a mast-mounted sensor package for electro-optical and infrared (EO/IR) imaging and automated classification of surface targets, which is tasked with collecting ISR data at the planned insertion site ("Harbor ISR" task). The UUV team also includes two other submersibles (UUV2, UUV3) which are used to verify and secure the planned insertion route via bottom-mapping and mine countermeasure operations ("Bottom Mapping/MCM" task). A small, rotor-based UAV (UAV1) located near the enemy harbor area supports communications between this UUV team and the LCS platform ("Comms" task). In addition to the UUV team, a second team of unmanned vehicles provides anti-terrorism and force protection support ("AT/FP" task) for the loitering LCS. This team includes an unmanned surface vehicle (USV1), a weaponized, rigid-hulled boat tasked with patrolling the area immediately surrounding the LCS to identify and intercept small vessels that may threaten the ship. The USV is supported by another small, rotor-based UAV (UAV2) that provides additional streaming video coverage of the area, as well as targeting support for engaging potential threats.

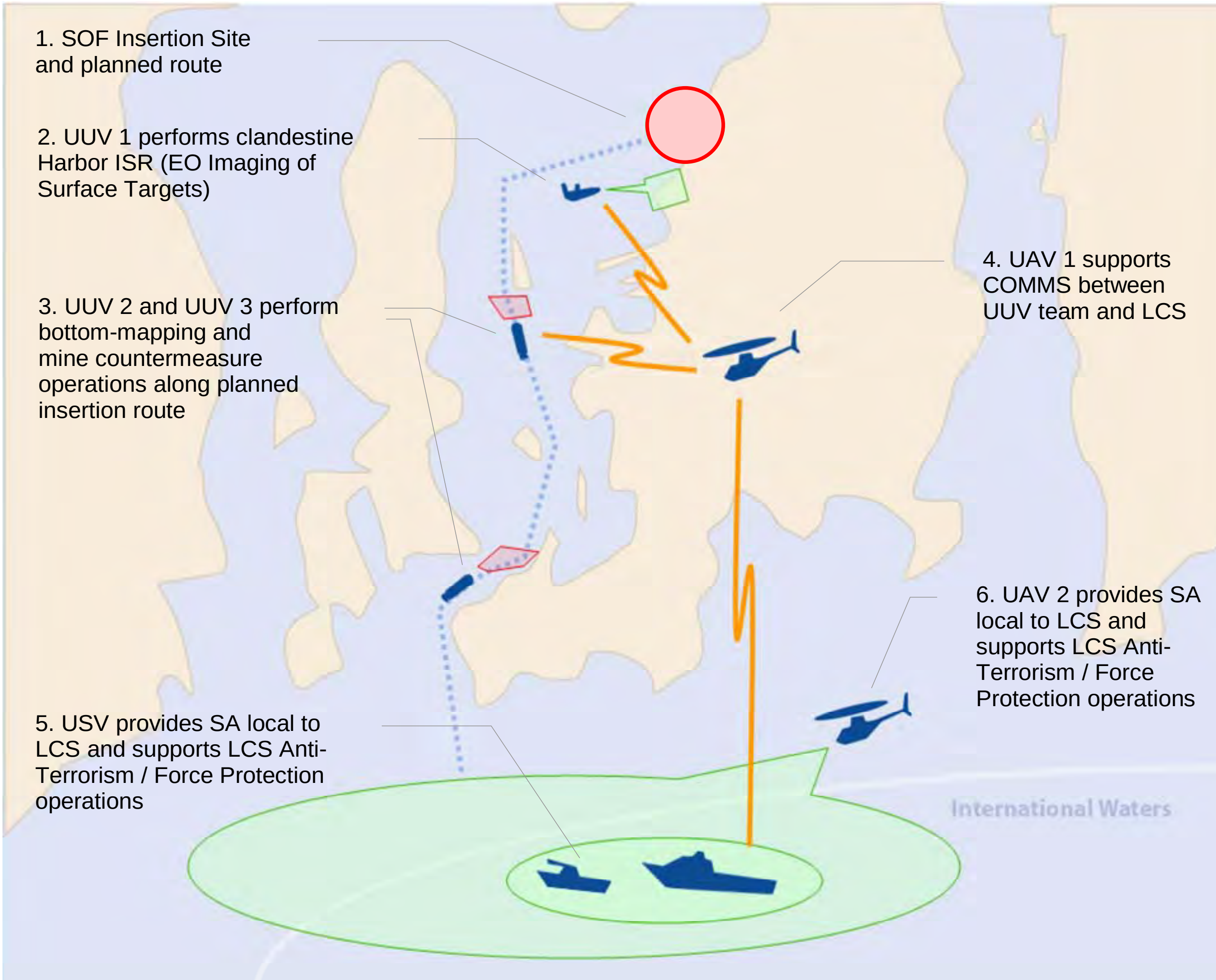


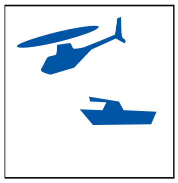
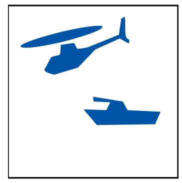
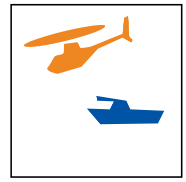
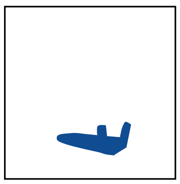
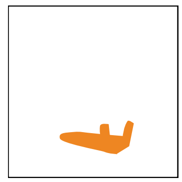
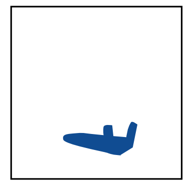
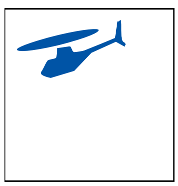
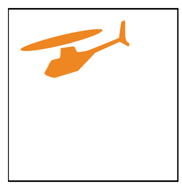
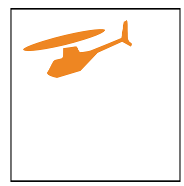
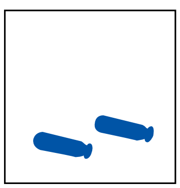
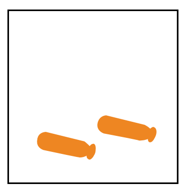
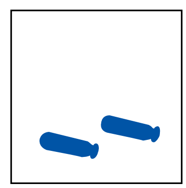
Figure 8. Extended operational scenario reflecting significant heterogeneity in a notional US Navy unmanned vehicle mission.

This operational scenario highlights four distinct tasks within the mission environment ("Harbor ISR," "COMMS," "Bottom-Mapping/MCM" and "AT/FP") and assigns specific unmanned vehicles to each of these tasks. The scenario does not, however, specify how the supervisory control of these vehicles (or tasks) is allocated amongst a team of one or more human operators. Rather, the scenario was designed to flexibly support the injection of a variety of notional strategies for vehicle control allocation across the overall team, each resulting in different types and levels of mission heterogeneity. Three of these strategies for control allocation are shown in Figure 9 and described below.

Single Operator Allocation: Under this operator allocation strategy, control over all vehicles is assigned to a single operator (Figure 9, Configuration 1). This allocation reduces the need for coordination between multiple human operators, but leads to a high level of mission heterogeneity. In this case, the single operator is tasked with supervising heterogeneous vehicles with heterogeneous capabilities, performing heterogeneous tasks in heterogeneous domains and geographical locations.

Task-Based Allocation: Under this allocation strategy (Figure 9, Configuration 2) vehicle control is distributed across a team such that responsibility for a particular mission task (e.g. AT/FP for the LCS) falls to a single human operator, regardless of the vehicles used. With this approach, heterogeneity of task—and likely heterogeneity of geographical space—is minimized. However, in this scenario, preservation of task homogeneity leads to

Table 9. Effects of vehicle and task allocation strategies on mission heterogeneity.

Operator A Operator B	**Configuration 1** Operator A responsible for all activities	**Configuration 2** Vehicle Allocation by Task / Sector	**Configuration 3** Vehicle Allocation by Domain
TASKS **LCS AT/FP** • LCS threat surveillance • Identification of tracks for interrogation / intercept • Interception			
Harbor ISR • EO/IR imaging above the surface for insertion recon • Bottom Mapping			
ISR / Comms • Maintenance of communications relay • MMTI, EO/IR imaging			
MCM/ Bottom Mapping • MCM for LCS path • Bottom mapping for insertion			
Notes	• High task complexity • High vehicle/domain heterogeneity • Domain A: Air/Water • Region A: LCS proximity, Harbor OPAREA • Tasks A: LCS AT/FP, Mapping/MCM, Harbor ISR, Comms	• High vehicle/domain heterogeneity (A, B) • Domain A: Air/Water • Domain B: Air/Water • Region A: LCS proximity • Region B: Harbor OPAREA • Tasks A: LCS AT/FP • Tasks B: Mapping/MCM, Harbor ISR, Comms	• High task/sector heterogeneity (A, B) • High vehicle heterogeneity (A) • Domain A: Water • Domain B: Air • Region A: LCS proximity, Harbor OPAREA • Region B: LCS proximity, Harbor OPAREA • Tasks A: LCS AT/FP, Mapping/MCM, Harbor ISR • Tasks B: LCS AT/FP, Harbor ISR, Comms

heterogeneity of vehicle type and operating domain. For example, the operator tasked with protecting the LCS must supervise both a USV and a UAV to perform the mission.

Vehicle-Based Allocation. Under this allocation strategy (Figure 9, Configuration 3) vehicle control is distributed across a pair of operators based on vehicle type or operating domain, regardless of the tasks being performed by that vehicle. In this scenario, one operator is responsible for supervising all water-based vehicles and the second operator is responsible for the aerial vehicles. In this case, vehicle heterogeneity is greatly reduced for each operator. However, task and location heterogeneity are increased. For example, although the second operator is only supervising UAVs, each vehicle is performing a separate task (e.g., AT/FP, COMMS) within a different sector of the operational area (local to the LCS and the enemy harbor, respectively).

Within this scenario, it is clear that the type and extent of mission heterogeneity experienced by mission operators will vary greatly with the strategy for asset allocation that is applied. What is not obvious, however, is how these different allocation strategies—and the resultant heterogeneity they impart—will impact the ability of individual operators to effectively and efficiently supervise the unmanned team, nor how these different types of heterogeneity can be best addressed through the design of supervisory control interfaces. For example, are there particular types of heterogeneity that will be more detrimental to performance than others? Will preserving task homogeneity at the cost of vehicle heterogeneity lead to greater operational performance than when vehicle homogeneity is preserved at the cost of task heterogeneity? In the following section, we describe the approach we are currently using to investigate these concerns.

B. Evaluating the Effects of Heterogeneity on Mission Performance

The mission scenario described above raises numerous concerns regarding the effects of heterogeneity—a product of the specific operational tasks, unmanned vehicles, and operator allocation for a given mission—on the efficiency and effectiveness of the human operator. For example: Will particular types of heterogeneity be more detrimental to mission performance than others? How can the cognitive complexities that will arise from different forms of heterogeneity be mitigated through interface design? In light of these concerns, we are extending our initial interface design effort to address comprehensive interaction solutions for the supervisory control of future heterogeneous unmanned vehicle teams. This effort includes a continuation of the previously described hybrid CTA and design process to account for the expanded mission scenario, which incorporates a number of new operational tasks and vehicles. In addition, this ongoing work will also employ: (1) a simulation-based modeling effort for a predictive analysis of how various types and levels of mission heterogeneity affect human and overall mission performance; and (2) a human-in-the-loop evaluation effort to rapidly investigate potential interface design approaches for addressing heterogeneity effects.

Our approach begins by developing a better understanding of how heterogeneity may potentially impact mission performance within mixed-initiative teams. To that end, we are constructing a framework that will identify different resource allocation strategies involved in the planning and re-planning of missions that require teams of unmanned vehicles. For example, one can consider the set of decisions involved in allocating each vehicle in the team to particular sub-tasks of the overall mission. The presence of heterogeneity in the vehicle team will affect the alternatives present for decision making related to such assignment. In homogeneous systems, where all the tasks and vehicles are identical, the alternatives for vehicle-task assignments are more limited than in the case where either one or both of vehicles and tasks are heterogeneous. An important implication of heterogeneity in unmanned vehicle teams is therefore an increase in the diversity of strategies that are available for vehicle/operator/task resource allocation.

To investigate the impact of heterogeneity on overall mission performance, we have chosen to first pursue discrete-event simulations of the previously described heterogeneous scenario so that the effects of heterogeneity in combination with mission planning/re-planning strategies can be analyzed. Our simulation-based approach will allow for a rapid investigation of the relative contributions of the many types and levels of mission heterogeneity highlighted earlier. The results from the simulations will be used as part of an effort to build a predictive model that can estimate mission performance as vehicle-team compositions along with resource allocation strategies are varied. As a by-product of the predictive model, planners will be able to optimize mission performance by varying one or more of the resource allocation strategies. We hope to use this model to provide the basis for decision support design that recommends to the mission planners and re-planners those strategies that are most appropriate for maximizing mission performance.

Based on the performance insight captured by this modeling effort, we will apply human factors design principles (e.g. Ref. 13, Ref 14.), to transform the information requirements from our expanded hybrid CTA into potential interface design concepts. These interaction design concepts will then be instantiated as limited-functionality software interfaces, using a variety of rapid prototyping methods. We will use these prototypes to

support a series of human-in-the-loop evaluations of the suitability and effectiveness of the interface design concepts in supporting supervisory control of heterogeneous unmanned vehicle teams in a simulated mission environment. The mission environment itself will be driven by an experimental testbed that we are currently developing to dynamically link the prototype display interfaces to unmanned vehicle behaviors and evolving environmental states. When possible, this testbed will leverage existing simulations of unmanned vehicle capabilities and behaviors, such as those being developed under the Navy's Intelligent Autonomy program, in response to the human subject's supervisory control actions. Where the use of futuristic or notional autonomous capabilities makes this simulation difficult or impossible, the testbed will support light-weight approaches to "faking" these capabilities through what are commonly referred to as "Wizard-of-Oz" experimental techniques. In this approach, a human operator—unseen by the experimental subject—serves as a proxy for the automation system, receiving input from the control interface and adapting vehicle behaviors appropriately.

This human-centered evaluation process will target specific slices, or vignettes, of the overall mission scenario, which will be selected, in part, based on predicted operator performances generated though the previous modeling analysis. For each of these vignettes, human subjects will use the prototype display interface to supervise some subset of the unmanned vehicle team in completing mission tasks and responding to dynamic mission events. The subset of vehicles under the operator's supervision will be manipulated to reflect the range of previously described vehicle and task allocation strategies. Using this approach, we will measure a variety of operator performance metrics, including overall mission performance, subjective mental workload, and response time, to address the effectiveness with which the prototype display interfaces address different types and levels of mission heterogeneity. Findings from this evaluation effort will be used to guide further design of potential supervisory control interface solutions, as well as to further evolve our operator performance models.

IV. Conclusions

Future military unmanned systems will be highly heterogeneous, relying upon different vehicles from a range of operating domains to collaboratively perform complex and dynamic mission tasks. While these systems will employ increasingly sophisticated automation, the human operator will continue to play a fundamental role as mission supervisor, overseeing vehicle activities, providing contextual insight as necessary, and responding to dynamic operational environments and mission goals. Heterogeneity in vehicle operating domains, performance characteristics, levels of automation, weapons and sensor capabilities, and even mission tasks will all contribute to the cognitive load placed on these operators. In this paper, we have introduced an effort to address these effects of heterogeneity through the design of human-centered information displays. We first presented the results of a cognitive task analysis and interface design effort for a simple unmanned vehicle team. Following this, we described the issues of heterogeneity and coordination of command across multiple vehicle teams as two key concerns in the development of effective and efficient interfaces for the supervisory control of unmanned systems. Finally, we introduced a combined simulation-based modeling and human-in-the-loop evaluation approach that we are pursuing to develop supervisory control interfaces that flexibly accommodate alternative command and control philosophies for heterogeneous unmanned vehicle teams. We are currently applying this approach in the development and evaluation of control interfaces for supporting future unmanned naval missions within the littoral combat environment.

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